ACI Sécurité Informatique CORTOS “ Control and Observation of Real-Time Open Systems ”

October 30, 2006

The web site of the project is `http://www.lsv.ens-cachan.fr/aci-cortos/`

1 CORTOS from an Administrative Point of View

The three following labs were parts of the CORTOS project:

- Institut de Recherche en Communications et en Cybernétique de Nantes (IRCCyN, CNRS UMR 6597 & École des Mines de Nantes & École Centrale de Nantes & Université de Nantes), Group MOVES,
- Laboratoire Spécification et Vérification (LSV, CNRS UMR 8643 & ENS de Cachan),
- VERIMAG (CNRS UMR 5104 & Université Joseph Fourier & Institut National Polytechnique de Grenoble).

The following people are involved of the project:

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The following theses have been defended during the project:

- Didier Lime (IRCCyN)
  - *Title:* Vérification d'applications temps-réel à l'aide de réseaux de Petri temporels étendus
  - *Grant:* European project EAST
  - Started in October 2001, defended on December 1, 2004
- Guillaume Gardey (IRCCyN)
  - *Title:* Vérification et contrôle des réseaux de Petri temporels
  - *Grant:* Alloc. MENRT
  - Started in October 2002, defended on December 8, 2005
- Houda Bel Mokadem (LSV)
  - *Title:* Vérification des propriétés temporisées des automates programmables industriels
  - *Grant:* Alloc. École Doctorale ENS Cachan
  - Started in September 2003, defended on September 28, 2006

The following theses are being prepared during the project:

- Fabrice Chevalier (LSV)
  - *Title:* Observation et contrôle de systèmes temporisés
  - *Grant:* AC ENS Cachan
  - Started in September 2004, defense expected in 2007
- Moez Krichen (VERIMAG)
  - *Title:* Testing for Real-Time Systems
  - *Grant:* Alloc. MENRT

  - Started in September 2004, defense expected in 2007

- Pierre-Alain Reynier (LSV)
  - *Title:* Modèles temporisés pour la vérification, implémentabilité et composition
  - *Grant:* AC ENS Cachan
  - Started in September 2004, defense expected in 2007

The following post-doctoral studies have been made during the project:

- Laura Bozzelli (LSV)
  - *Grant:* CORTOS post-doc
  - Started in October 2005, ended in May 2006
- Julien d'Orso (IRCCyN)
  - *Grant:* CORTOS post-doc
  - Started in January 2004, ended in December 2004

2 Our Results

The results we have obtained roughly follow the lines of our initial project statement, and some additional works have been done. We will describe the main results we have obtained in this project.

2.1 Observation of Systems

Observation of Real-Time Systems. Observation lies at the heart of many problems, including control. Indeed, although control is a more general problem than observation in terms of decidability and complexity, solving the control problem is most of the times not harder than solving the observation problem.

In the case of real-time systems modeled as timed automata, a crucial assumption made in previous work on controller synthesis is that the controller is state-feedback, that is, can observe the complete state of the system under control, including discrete variables and clocks. In a 2002 paper by Stavros Tripakis (before the project started), we showed that this assumption can be relaxed, at least in the case of monitoring for purposes of fault detection. We showed that it is possible to synthesize observers using an on-the-fly subset construction technique, consisting in computing the set of all possible states the automaton can be in, given the current observation.

In the course of this project, we have developed the above mentioned ideas further and applied them to monitoring [BBKT05] and testing [KT04a, KT04b, KT05a]. Testing is very similar to control, in that both can be seen as games. In control, the game is played between the controller and the plant: the controller tries to maintain or achieve a given specification, while the plant "tries" to prevent the controller from doing so. In testing, the game is played between the tester and the system under test (SUT): the tester tries to show that the SUT is non-conforming to the specification, while the SUT tries to prevent the tester from doing so.

We have also extended existing work on the observation problem by synthesizing observers as deterministic timed automata (DTA) [Che04, BCD05]. In this setting, the observation problem is modeled as a game between the environment and the observer and we give algorithms for synthesizing observers that are various types of DTA, *e.g.* DTA and event-clock automata when the observer has bounded resources.

Along the same lines we have studied the monitoring and diagnosis problems using *digital clocks* [ACT06]. In this setting the plant is modeled by a timed automaton. A digital clock is also modeled by a timed automaton and issues a special event *tick* at particular date. The composed system Plant and digital clock thus generates timed words. The role of the monitor (resp. diagnoser) is to monitor (resp. diagnose) the plant without using any quantitative information *i.e.* using only the untimed version of the timed words. In this sense, this problem can be stated as follows: given a plant and a digital clock, is there a finite automaton (fed with untimed words generated by the plant in parallel with the digital clock) that can monitor (or diagnose) the plant ? A solution to this problem and to other related extensions has been proposed in [ACT06].

Decentralized observation problems. Observation and control is quite well understood for untimed systems in the centralized case, that is, where a unique controller is assumed to control the entire plant. All the work on observation and control for timed systems also assumes a centralized framework.

In this research axis, we study problems of decentralized observation and control, where a number of observers/controllers act in parallel for a given plant. Initially, we focus on observation, which is often a necessary first step in order to understand control. Moreover, in recent work [Tri04] we have shown that some decentralized observation problems are undecidable and can also be used to show undecidability of control problems. In [Tri05b, Tri05a] we have extended our study to problems of distributed observation with bounded or unbounded memory and proved several (un)decidability results and proposed algorithms for synthesizing distributed observers.

State identification problem. State identification is a class of fundamental problems of testing, consisting in inferring unknown information about a system such as its current state or its past (initial) state, by performing input/output experiments on the system, given some knowledge of the system behavior (typically a model of the system such as an automaton). While these problems have been well-studied for finite-state machines such as Mealy or Moore machines, they have not been studied for more powerful models. In the context of CORTOS we have begun examining these problems for two types of extended models: timed automata and finite-state transducers. Timed automata have been explained above and is the de-facto model for real-time systems. Finite-state transducers extend Mealy machines by allowing inputs and outputs to be "desynchronized". In other words, a single input symbol may produce a sequence of 0, 1 or more output symbols, rather than a single output symbol. This model is useful as an abstraction of timed models, in particular discrete-time models. We have provided preliminary results on the state identification of timed automata in [KT05b] and transducers in [KT06].

2.2 Control for Time Petri Nets (TPN)

Scheduling. Hard real-time systems are usually designed as several tasks interacting and sharing one or more processors. Hence, in a system S, tasks have to be scheduled on the processors in such a way that they respect some properties P imposed by the controlled process. This is usually achieved using either an offline or an online approach.

We consider an extension of TPNs, namely scheduling-TPNs, that allows to take into account the way the real-time tasks of an application distributed over different processors are scheduled. This model allows us to model preemption and resumption of actions in time-dependent systems and is based on the concept of stopwatches. We have proved [BLRV05] that the (state) reachability problem is undecidable for a simple class of TPNs extended with stopwatches, even when bounded. This result can be easily generalized to known extensions of TPNs allowing preemption and resumption of transitions [RL04, LR04]. Concerning the analysis of scheduling-TPN, in [LR04], we tackle the problem of the state space explosion using a fast DBM-based algorithm which overapproximates the set of reachable states. This overapproximation is used in [LR06] to compute a stopwatch automaton timed bisimilar to the initial scheduling-TPN and which can then be analyzed using a tool like HyTech.

Safety control synthesis on TPNs. Unlike timed automata which have a finite discrete state-space structure (locations), the set of reachable markings of a TPN is generally infinite and this property is undecidable. We study some control synthesis problems on an extension of TPNs that model a plant and its environment. The TPN control model both represents controllable and uncontrollable events, the problem is then to design a function (controller) such that a given property is fulfilled. We focus our analysis on safety properties expressed on the markings of the net and we propose a symbolic method to decide the existence of a controller that ensures this properties. Unlike existing methods on TPNs, that assume the net is bounded, the method is applicable for any TPNs and we prove in particular that existence of a controller which k-bounds the plant is decidable. This work has been published as [GRR06].

Non-interference of TPNs. The non-interference problem is to control explicit or implicit information flow, through which observers could gain secret or sensitive information, either maliciously or inadvertently. It is well known that information can be retrieved in an implicit way from the variations of time intervals between message transmission, thus involving observation of quantitative timing information. Hence, abstracting time constraints from an interferent timed model could yield a non interferent untimed model. However, up to now, only a few researchers have tackled the question of timed non interference and they do not directly address the questions of verification and control. In [GMR05], we discuss a notion of non interference for dense real-time systems that refines notions existing in the literature and investigate decidability issues raised by the verification problem for dense time properties. We then prove the decidability of the problem of synthesis of the timed controller for some of these timed non-interference properties (State Non Interference and Cosimulation Non Interference), providing a symbolic method to synthesize a controller that ensures them.

2.3 Control of Extended Classes of Systems

Hybrid controller synthesis. In this work, we developed a method for hybrid controller synthesis through the study of an engine control problem, namely, idle speed control. The model of the car engine is a hybrid automaton with both continuous and discrete inputs. One important control objective is to maintain the speed of the car within some desired range (around the reference value). This problem is known to be difficult due to unpredictable external disturbances (for instance, load variations).

The safety controller we want to design is hybrid in the sense that it comprises a continuous law (for the throttle angle), and a mode switching law (the decision between positive and negative sparks). Such controllers can be derived from the maximal invariant set; however, it is hard, both theoretically and practically, to compute this set for a nonlinear hybrid system with both continuous and discrete control inputs. For effective computation purposes, we restrict the continuous laws to be in a class of piecewise constant functions with uncertain interval. Furthermore, using the cascade structure of the system, we apply the compositional assume-guarantee reasoning from model-checking to this controller design process.

In addition, the use of piecewise constant control inputs allows to take into account optimality criteria (such as minimizing gas consumption). We have also studied the problem of quantifying the performance loss due to the use of piecewise constant control in this specific car control problem as well as in a more general context. More details on the results of this work can be found in [Dan05].

Control of transfinite sequences. Ordinal automata allow to model (physical) systems admitting Zeno behavior: infinitely many actions in a finite time. This is relevant when the environment evolves much quicker than the controller. We have introduced a logic LTL(ω^k) —as an extension of LTL— to reason about transfinite sequences. Every sentence of LTL(ω^k) can be translated into the First Order Logic with the ordering relation [Cac06]. This result can be refined by showing that model checking and satisfiability problems for this logic (and ordinal automata) is EXPSPACE-complete when integers are represented in binary [DN05, DN06] and PSPACE-complete with a unary encoding. To control such systems we assume that the controller works on ω-sequences: the environment performs ω^{k-1} actions between two actions of the controller. We have solved this control problem using game techniques [Cac06]. Because of the unobservable actions and of the different time scales, the controller cannot fully observe the current state of the system. That is why, the game we consider deals with imperfect information.

Control of o-minimal hybrid systems. O-minimal hybrid systems are a class of hybrid systems which enjoys interesting computability properties like the finiteness of the coarsest time-abstract bisimulation, the decidability of reachability properties (under the hypothesis that the underlying theory is decidable). Moreover this model is suitable for representing phase phenomema, and we have studied this model in the context of control and open systems. We have proved rather surprising results like the non-soundness of time-abstract bisimulation w.r.t. control problems, but the soudness of the prefix partition, a refinement of the time-abstract bisimulation [BBC06b]. This general result allows to recover the special case of timed automata.

Control of linear-time properties. Many works on control problems focus on the choice of the models for the systems, and consider only simple properties like reachability or safety properties (and possibly other state-based properties). In this work, we have focused on the basic model of timed automata but considered a more expressive language for expressing properties (or control objectives). We have indeed considered MTL, a timed extension of the classical LTL formalism, whose model-checking has been proved decidable by Joël Ouaknine and James Worrell recently. Unfortunately the control problem becomes undecidable for MTL properties, and it is required to fix the resources of the controller to be able to synthesize controllers for MTL [BBC06a].

2.4 Logics for Control

Timed modal logic for controllability. In the untimed framework solving a μ-calculus model-checking problem is equivalent to solving the control problem for plants expressed as finite automata. This equivalence is highly used and important. We have then proposed an extension of this reduction to the timed framework [BCL05] and have used the timed modal logic L_ν to express timed control objectives. We have shown that the control problem for a large class of such objectives can be reduced to a model-checking problem for an extension of the logic L_ν with a new modality (which is proved to be necessary to express control problems). We have also proved that model-checking this new logic remains EXPTIME-complete and integrated it in the model-checker CMC (which implements a compositional model-checking method for L_ν).

Multi-agent systems. Multi-agent systems extend classical two-player games, and are thus especially interesting for modelling and reasoning about systems that are controlled by several (coalitions of) agents. In that setting, ATL is an extension of the branching-time temporal logic CTL that provides a way of dealing with the existence of strategies of some coalition to achieve some goal.

After revisiting the original papers on ATL and refining some expressiveness and complexity results in the classical, untimed framework [LMO06a], we begun extending this framework to "durational" models, i.e., models whose transitions are decorated with (intervals of) discrete durations. We proved that, when no equality constaint is involved, model-checking a timed extension of ATL on those systems remains in PTIME when no equality constraint is involved, while equality constraints makes the problem EXPTIME-complete [LMO06b].

2.5 Optimal Timed Control

Optimal reachability control. One important problem in control is also to optimize the consumption of resources: one wants to control a system but using as few resources as possible. In the case of the reachability control problem and if the resource is time, the aim is to force the environment to reach a particular state q as quickly as possible. The optimal time the controller can guarantee is thus the value t^* s.t. whatever the environment does the controller can guarantee to reach state q within t^* time units, and it cannot guarantee this for any $t < t^*$. The previous problem is known as the "optimal-time reachability control problem" and has been solved in 1999. We have studied a more general version of the problem, namely the cost-optimal control problem, where the resource is more general than time. We have defined the model of priced timed game automata (PTGA) and given conditions under which optimal cost is computable [BCFL04]. We have implemented a polyhedra-based algorithm using the tool HyTech [BCFL05] for computing the optimal cost of winning for this class of systems. Following our work, Jean-François Raskin *et al* have proved that computing optimal cost is in general undecidable, and we have sharpened their result and proved that the problem is decidability even with timed automata with as few as three clocks [BBM06]. On the other hand, we have proved that optimal cost is computable when restricting to one-clock timed automata [BLMR06]. The paper [Bou06] surveys all these results.

Optimal infinite schedules. In works presented above, control objectives are "reach a given set of states". We have also considered safety control objectives where the aim is to optimize mean cost along schedules of the system, and first restrict to closed systems where all actions are supposed to be controllable. To cover a wide class of optimality criteria we have introduced an extension of the (priced) timed automata model that includes both costs and rewards as separate modelling features. With that model it is easy to express properties like "find infinite schedules where the cost by time unit is minimal" or "find infinite schedules where the cost by action is minimal", etc. We have subsequently shown that the derivation of optimal infinite schedules for this model is computable. This is done by a reduction of the problem to the determination of optimal mean-cycles in finite graphs with weighted edges. This reduction is obtained by introducing the so-called corner-point abstraction, a powerful abstraction technique of which we show that it preserves optimal schedules [BBL04, BBL06]. As further important developments, we aim at solving the problem in the presence of an adversary (*i.e.* when some actions are not controllable).

2.6 Applications of Control Problems

Implementability of timed automata. Timed automata are a mathematical model used for modelling real-time systems. In particular, they are in some sense an idealization of those systems, in that they assume infinite precisions and perfect synchronization of the clocks, which is not the case in any physical model. We investigated two directions for dealing with this issue:

- the first direction relates implementability with robustness [BMR06]: the guards of the timed automaton are "enlarged" by some parameter Δ, and the original automaton robustly satisfies a property iff the exists some positive Δ for which the enlarged automaton also satisfies the property. This approach was initiated by Jean-François Raskin for reachability properties, and we extended it to any LTL property;
- the second direction aims at directly encoding the imprecisions of the system in the model [AT05]. This approach is much more powerfull, and can for instance encode delays in communications of different modules of the model. Unfortunately, it still has some limitations, and does not enjoy the "faster-is-better" property, stating that if a model can be safely implemented on some hardware, then it should also be implementable on faster hardware. However, there is some hope that some instanciation of this general framework could be relevant for implementability issues.

Application of controller synthesis to Aspect Oriented Programming (AOP). In this work, controller synthesis is used as a conceptual tool to specify and understand aspect oriented programming (AOP) in a formal framework. It aims at providing new facilities to implement or modify existing programs: implementing some new functionality or property in a program P may not be done by adding a new module to the existing structure of P but rather by modifying every module in P. This kind of functionality or property is then called an aspect. AOP provides a way to define aspects separately from the rest of the program and then to introduce or "weave" them automatically into the existing structure.

The goal of this work is to study a notion of aspects for reactive systems. As weaving an aspect into a program P introduces some modifications of the behavior of P, and as we deal with critical systems, our notion of aspect needs to be semantical. Ideally, in a formal framework, when defining an aspect A

for a program P, one should be aware of what the weaving of A into P implies on the behavior of the woven program *i.e.* (1) what A changes and what is ensured by the new behaviors; (2) what A does not change w.r.t. P, namely which property of P is preserved when weaving A. (Among these properties, some form of equivalence preservation should of course at least be ensured.) Both (1) and (2) can be interpreted as a controller synthesis problem. We are currently working on that interpretation to better understand the AOP framework [AMS04, AMS05].

Scheduling of multi-threaded real-time programs using geometry. In this work [GD04] we examined the behavior of a class of multi-threaded programs, from the point of view of the worst-case response time. We defined a timed version of PV programs and diagrams which can be used to model a large class of multi-threaded programs sharing resources. PV programs and diagrams, introduced by Dijkstra, are models for geometrically describing interactions of concurrent processes and have been used for the analysis of concurrent programs. We also introduced the notion of the worst-case response time of a schedule of a timed PV programs. This framework can be used to compute efficient schedules for multi-threaded programs on a limited number of processors. In particular, to tackle the complexity problem, we defined an abstraction of the optimal schedules and developed a method to construct this abstraction in order to compute efficient schedules as well as an optimal one. This method is based on a geometric realization (or geometrization) of the timed PV program and a spatial decomposition of the geometrization. An experimental implementation allowed us to validate the method and provided encouraging results.

We are currently working on a new method for computing an optimal schedule, which exploits further the geometry of the timed PV programs. We show a relation between continuous properties of the geometrization and the abstraction of the optimal schedules. This relation can be used to solve the scheduling problem more efficiently.

3 CORTOS in France and Further

The project CORTOS has been committed in several national and international events (chronological order):

- A course on the control of timed systems has been given at the Spring School on Infinite Games (organized by the european network GAMES) by Patricia bouyer in March 2004.
- A tutorial on timed control at a meeting of the AS 155 du RTP 24 "Approches formelles pour l'analyse et la synthèse sûre de contrôle des systèmes dynamiques hybrides" has been given by Franck Cassez in September 2004.
- An invited session of the French conference MSR'05 (September 2005) has been devoted to the control of timed systems, and three talks have been

given by members of the project. We have published three survey papers in the proceedings of the conference [ABC+05, BCKT05, AMRT05].

- A survey on the control of timed and hybrid systems has been published in the "Concurrency Column" of the "Bulletin of the EATCS" by Patricia Bouyer and Fabrice Chevalier [BC06].
- The workshop GDV'06 (Games in Design and Verification) has been co-organized as a satellite event of CAV'06 (Seattle, USA, August 2006) by Patricia Bouyer.
- We have organized the **workshop CORTOS'06** in August 2006 as a satellite event of CONCUR'06 (Bonn, Germany). This was the workshop we promised to organize as the achievement? of our project. Speakers at that workshop were all invited and were Thomas Brihaye (UMH, Belgium), Kim G. Larsen (Aalborg University, Denmark), Jean-François Raskin (ULB, Belgium), Goran Frehse (Verimag, France), Franck Cassez (IRCCyN, France) and Patricia Bouyer (LSV, France). The program of the workshop is available on the web site: `http://www.lsv.ens-cachan.fr/aci-cortos/workshop-concur06/`.

4 What Next?

In March 2006, we have organized a joint meeting with ACI Persée and ACI Versydis (both are projects of the program ACI Sécurité Informatique 2003), and we have altogether written a proposal for the program ARA of the ANRA this year. We want to benefit from the work we have done within the three ACI projects and gather our skills to achieve a more ambitious project on the control of timed and distributed systems.

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